Stream Dynamics: An Overview for Land Managers

Burchard H. Heede

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Abstract

Concepts of stream dynamics are demonstrated through discussion of processes and process indicators; theory is included only where helpful to explain concepts. Present knowledge allows only qualitative prediction of stream behavior. However, such predictions show how management actions will affect the stream and its environment.

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Burchard H. Heede, Principal Hydraulic Engineer
Rocky Mountain Forest and Range Experiment Station[1]

[1]Headquarters at Fort Collins, in cooperation with Colorado State University. Research reported here was conducted at the Station's Research Work Unit at Tempe, in cooperation with Arizona State University.

Contents

	Page
Introduction	1
Scope and Purpose	1
Characteristics of Streams	1
The Basic Fluvial Process	1
Subcritical Versus Supercritical Flow	1
Froude Number	2
Laminar Versus Turbulent Flow	2
Reynolds Number	2
Sediment Transport	3
Interdependency of Hydraulic Variables	6
Equilibrium Condition and Adjustment Processes	6
Dynamic Equilibrium	6
Complex Channel Response	7
Major Adjustment Processes	7
Processes Affecting Channel Pattern and Shape	8
Bar Formations	8
Channel Patterns	11
Channel Shapes	15
Width-Depth Ratio	16
Shape Factor	16
Avoiding Pitfalls of "In-Stream Flow" Investigations	17
Channel Banks	18
Processes Affecting Longitudinal Profile	18
Longitudinal Profile Relationships	18
Aggradation	19
Degradation	21
Armoring	21
The Need to Monitor Stream Behavior	23
Conclusions	24
Literature Cited	24
Notation	26

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INTRODUCTION

Scope and Purpose

A land manager should understand general concepts of stream behavior to be aware of how management actions affect streams, since such actions can influence streams drastically. For example, vegetation cover manipulations on a watershed can increase water yield (Hibbert 1971), or streamside forest removal can activate bedload transport (Heede 1977). Streams are dynamic systems that are prone to change even without human interference (Heede 1975); change in the system itself may bring about adjustment once a geomorphic threshold has been reached (Schumm 1974). Thus, land management-stream interactions are complex.

Other professionals who need a general understanding of fluvial processes are hydrologists, civil engineers, fishery biologists, and plant biologists. Plant biologists might be concerned with riparian vegetation interactions with the stream, while the fishery biologist works in the stream itself. The hydrologist, on the other hand, is concerned with precipitation input into a watershed, its concentration in channels, and the mode, quantity, and quality of flow discharge. The civil engineer is more likely to be concerned about scour at bridge piers (degradation), or loss of discharge capacity by deposition (aggradation).

Knowledge of stream dynamics will help to point out what information is needed to characterize stream conditions, and what indicators suggest about present and future stream behavior. With this knowledge, professionals engaged in land management will be able to estimate what, where, and when effects of their actions will take place.

General understanding of fluvial concepts should also help managers recognize if a particular situation demands attention from an expert in river science (a potamologist). Unfortunately in many situations, stream data are either nonexistent or cover only flow rates and yields, but do not characterize present conditions or make well founded projections possible (Heede 1979).

High- and low-flow conditions have different requirements for conveyance of the water. If flow changes drastically, the channel often does not meet the new requirements, and adjustments must be made through stream-erosion processes. Well known examples are channel bed degradation or channel meandering.

This report presents a general outline of water flow and sediment transport as basic to all channel changes. It describes stream equilibrium condition and the required adjustment processes if equilibrium is lost. These processes lead to alignment, shape, or profile changes.

The user should be acquainted with the basics of flow and sediment transport and should recognize the strong interdependency between practically all hydraulic variables. Arrangement of this text permits the reader to consider only those processes of interest. The Literature Cited section will suffice or provide a starting point for in-depth study of specific processes or theories.

Characteristics of Streams

We usually think of a stream as one entity with a specific characteristic, such as the mighty Mississippi, the unpredictable Platte River, a small artery of a large stream system, or a bubbling mountain brook. But these same streams are very different at different times. At high-flow stage, for instance, mountain brooks are anything but bubbling waters. At low-flow regime, they meander sluggishly between channel banks, often filling not more than a fraction of the total bed. But at high-flow regime or flood stage, the channel may be totally filled or even too small, flood plains become water covered, and meanders straighten to convey the rushing waters most quickly.

If we would analyze the hydraulic variables of these two types of flow, we would have to conclude the character assigned to the stream is based on a single aspect and not on its complexity, because two different streams may be represented if low- and high-flow regimes are considered. Although the argument may appear merely semantic, in reality it is deep seated, since different processes are operative in both streams. Even to the casual observer, stream systems are dynamic.

THE BASIC FLUVIAL PROCESS

Subcritical Versus Supercritical Flow

Natural streams convey their water in different modes. At times, or in certain channel reaches, the flow is tranquil (subcritical) exerting low energies on banks and bed; at others, shooting (supercritical) flows occur which energies may damage an unprotected channel. Human activities can cause undesirable high-energy (supercritical) flows. For example, encroachments into the channel by diversion structures or bank revetments can narrow the channel. As a

consequence, the area of flow may decrease to the point where shooting flows occur. Knowledge of flow regimes, describing the flow characteristics in terms of available energies, therefore is required to recognize problems in channels or proposed channel improvements.

Fortunately, subcritical flow is the more common type of flow (fig. 1). Available energy of such flows is less than that of supercritical flows of the same discharge. The total energy of a flow (total head of flow) can therefore be better conserved in subcritical flow (Koloseus 1971). Maintenance of total head is important for channel stability as well as for structures such as water diversions.

In contrast, supercritical flow is undesirable because of its great erosive power due to high velocities (fig. 2). Also, higher stagnation pressures of supercritical flows can develop uplift forces of such magnitude that canal linings and concrete diversion structures have been removed (fig. 3) (Koloseus 1971). Stagnation pressure is the sum of the pressure intensity in a zone of uniform motion and the rise in pressure intensity due to channel obstruction or other changes.

Supercritical flows can also cause standing waves, produced when two equal waves travel in opposing directions. Standing waves may reach magnitudes requiring prohibitively high canal walls or diversion ditchbanks. Standing waves must also be considered where narrowing of channels by human works is planned. As a general rule, stream reaches with supercritical (shooting) flow should be avoided for structural installations, and this type of flow should not be created by channel manipulations (narrowing).

Froude Number

The Froude number (Fr), a dimensionless parameter, offers a quantitative measure to determine if subcritical or supercritical flow will occur. This number represents the ratio of inertial to the gravitational forces and is given by:

Figure 1.—Downstream view of the Verde River north of Phoenix, Ariz. The flow is subcritical (tranquil).

$$Fr = \frac{V}{\sqrt{gd}}$$

where V is the average velocity in the cross section of measurement, g if the acceleration due to gravity, and d is the average water depth. If inertia is smaller than the gravitational force, Fr<1, and flow will be subcritical (fig. 1), the flow will be supercritical if the ratio reverses and Fr>1. Critical flow, required for many artificial stream-gaging stations, has a Froude number of 1, but seldom will occur in natural channels. This regime is very unstable and generally occurs only for very short periods of time as a transitional stage between tranquil and shooting flows. The prevailing streamflow is subcritical and will show a relatively smooth water surface, except for waves created by winds, protrusions or large boulders and bedrock that lead to sudden decrease of stream depth (fig. 2).

Laminar Versus Turbulent Flow

Flows can also be characterized by the movements of individual fluid elements with respect to each other, which result in either laminar or turbulent flow. The major distinction is that, in turbulent flows, a complex secondary motion is superimposed on the primary (laminar) motion of the fluid elements (Rouse 1950).

In laminar flow, each fluid element moves in a straight line with uniform velocity. There is no diffusion between the layers or elements of flow, and thus no turbulence. In contrast, turbulent flow has a complicated pattern of eddies, producing random velocity fluctuations in all directions. These are caused by continuous interchange of finite masses of fluid between neighboring zones of flow. The phenomenon results in a disruption of the entire flow pattern; a current meter immersed in a turbulent stream shows continual deviations from the mean value. Obviously, constant changes of flow lines lead to surges of flow against banks and structures, increasing flow impacts. Turbulent flow is the normal condition in streams.

Reynolds Number

Movements of the fluid elements depend on the inertial and viscous forces. The latter, in a loose sense, could be envisioned as an expression of internal friction of the flow. The Reynolds number (Re) is a dimensionless measure of these forces:

$$Re = \frac{Vd}{\nu} = \frac{\textit{inertial force}}{\textit{viscous force}}$$

where ν is the kinematic viscosity represented by the ratio μ/ϱ; μ is the absolute viscosity and ϱ the fluid density. For natural channels, the critical value dividing laminar from turbulent flow is near a Reynolds number of 2,000; values less than 2,000 generally indicate laminar and those over 2,000 indicate turbulent flow.

Figure 2.–A constricted segment of the Salmon River, Idaho. The view is downstream. Note waves are traveling upstream (toward the viewer).

In summary, most natural streams have subcritical flow (Fr = <1). Also, turbulent flow (Re = >2,000) prevails over laminar flow (Re = <2,000).

Sediment Transport

Sediment transport is very complex. At least 30 variables are locked into the sedimentation processes, and the degree of interdependency between these variables is not fully understood. It is not surprising, therefore, that a reliable numerical method for determining bedload transport in alluvial streams is not yet available (Bogardi 1974, p. 17). Available methods are based on empirical relationships between a selected number of variables or require prerequisites based on assumptions not necessarily valid for the conditions.

Figure 3.—High stagnation pressures from shooting flows of the unusual January 1979 flood in the Verde River, central Arizona, created uplift forces that aided in upsetting this water-diversion structure and a 2-foot-diameter concrete pipeline.

For stable channels, Lane (1955a) demonstrated the qualitative relationships between sediment discharge (Q_s) and water discharge (Q_w) as a balance (fig. 4)

$$Q_s D \propto Q_w S$$

where D is the sediment particle size and S represents the slope. Lane's balance illustrates the intricate stream adjustment processes. If one side of the balance changes, the other must adjust to maintain equilibrium. Thus alterations in sediment or water discharge require changes in grain size and/or slope. For example, if the slope is increased, the stream will attempt to transport larger particles, or if stream discharge decreases, sediment load must decrease also to maintain balance. Otherwise, degradation or aggradation of the streambed will occur, respectively, as indicated by the figure.

For his balance, Lane selected as sediment discharge (Q_s) the coarser part of the sediment load, or more exactly the bed material load. He defined bed material load as the sediment in transport of sizes readily available in considerable quantities in the streambed. It is the coarser material largely molding the bed formation. He argued, "in most cases, the quantity of the fine load of silt and clay sizes can change almost indefinitely without materially affecting the river profile." We know now there are exceptions to this rule, such as when extremely large loads of fine material (wash load) are available. Heavy concentrations of fines cause a higher apparent viscosity of the fluid, which in turn results in increased transport

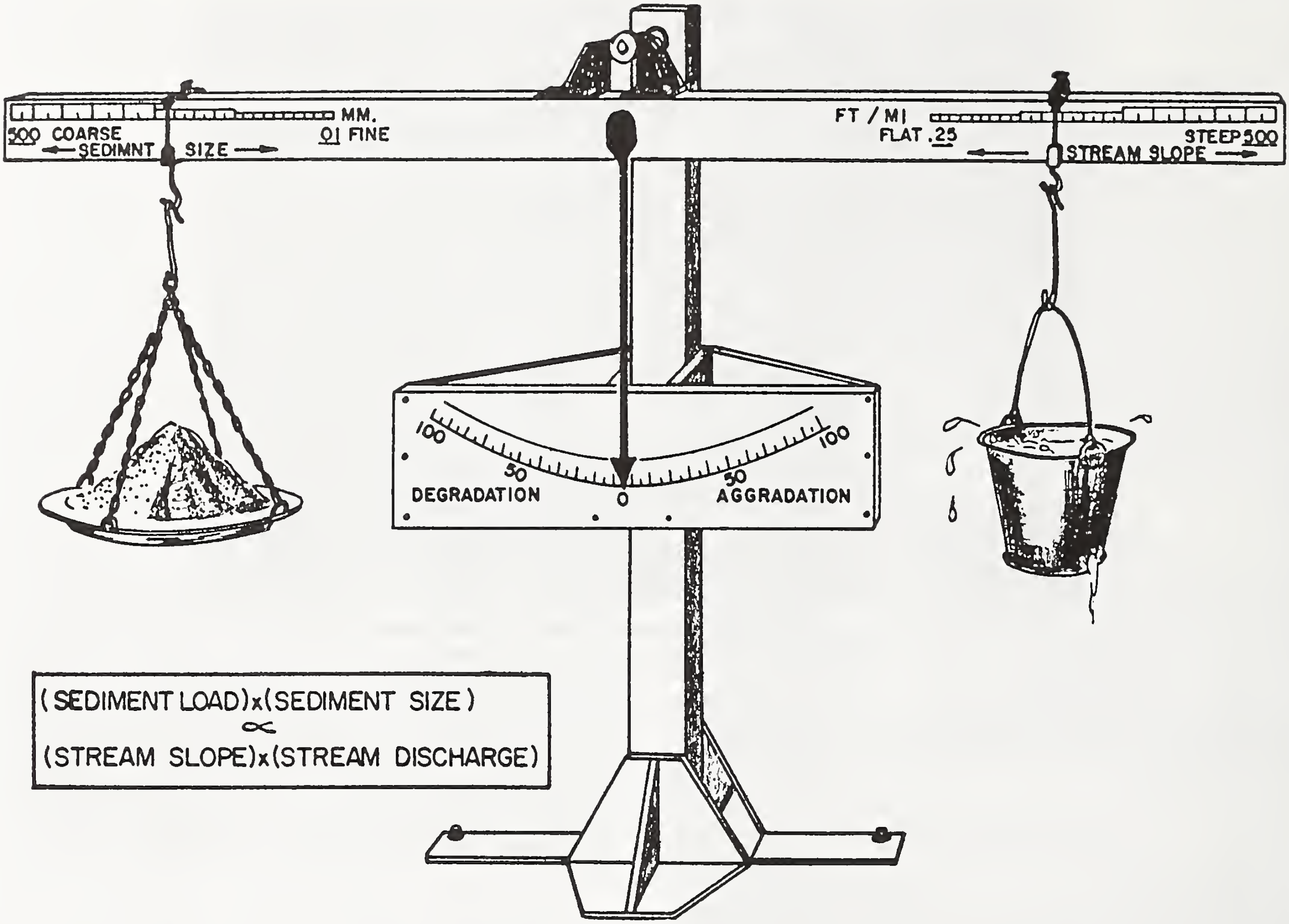


Figure 4.—Stable channel balance. (Sediment loads times sediment size) varies as (stream slope times stream discharge). (Courtesy of the American Society of Civil Engineers; from Lane, E. W. 1955. The importance of fluvial morphology in hydraulic engineering. American Society of Civil Engineers Proceedings Hydraulic Division 81:745-1 to 745-17.)

capacity for sediment. More and larger particles can be transported, which in turn affect the stream profile. An extreme condition, illustrating the viscosity influence (Bull 1968) in addition to the relatively high specific gravity of the flow mixture (Crandell 1968), is a mudflow carrying room-size boulders like soap bubbles. Johnson (1970, p. 461) suggested that lift forces may also be involved.

Flume experiments by Simons et al. (1963) demonstrated that clay in suspension affects viscosity, bed form, and flow resistance. With clay suspension, the total sediment load increased, which in turn affected the bed form. Since bed forms influence flow resistance (Simons and Richardson 1966), they enter directly into the hydraulics of the flow. Again, the interdependency of the processes illustrates the difficulty, if not impossibility, of quantitatively predicting the stream environment.

Water temperature also influences sediment transport capacity more than many investigators recognize. As temperature decreases, viscosity increases, and carrying capacity increases (Colby 1964). For example, when Colby dropped water temperature from 80° to 40° F, the sediment discharge for sand sizes ranging from 0.125 to 0.250 mm increased by 254%. The size class is common for riverbed sand.

Field investigations confirmed the temperature-sediment transport relations and their vital influence on stream behavior. In the Lower Colorado River for a given discharge, the sediment loads were 2.5 times greater in winter than in summer (Lane et al. 1949). Fahnestock and Maddock (1964) reported a change in water temperature of about 35° F from March to August significantly affected the hydraulics of flow and bed form in the Rio Grande River near El Paso, Tex. At some similar discharges, mean velocity was greater in March and the bed was plane, whereas mean velocity was less in August and large dunes developed on the bed (flow resistance increased with dune formation).

Management implications based on the temperature-sediment relations are many. Where data on annual sediment loads are required, best results will be

obtained by sampling during summer and winter. Winter data of one stream should not be related to summer data of another. Most land management actions result in increased water temperatures and, therefore, decreased sediment loads. Under extreme conditions, this could lead to aggradation.

From many observations it has been found the sediment load in natural streams varies roughly as the square of the discharge (Lane et al. 1949). This approximation is expressed by the equation

$$Q_s = K_a Q^2_w$$

where Q_s is the sediment load in tons per day, Q_w represents the water discharge in cubic feet per second, and K_a is a coefficient that normally changes from stream to stream and with the season. The K_a coefficient could be helpful for approximating future sediment loads if used with flow frequency curves (differentiated between winter and summer flows), because some probabilistic aspects of sedimentation would be taken care of. Because the variation in the original data will generally be large, long periods of record are required to obtain meaningful averages. The length of record required depends on the degree of uniformity in the particular stream system.

Differences between sediment transport capacity and actual sediment load lead to deposition or scour (Lane 1955b). In other words, sediment is stored or depleted in a given reach, resulting in nonuniform flow of sediment. Uniform sediment flow represents equilibrium condition and satisfies the continuity principle of sediment (Vanoni et al. 1961). If actual sediment discharge differs from the equilibrium sediment discharge, the stream will try to adjust the actual to the equilibrium discharge. Both the actual rate of transport and the equilibrium rate will change, but they will tend to approach each other. Uniformity of sediment discharge must be considered over time, because sediment often moves in a wave-like mode, especially if movable bed forms such as dunes are present.

In many instances, works of humans distort uniform sediment flow. Best known examples are river dams causing a decrease of equilibrium transport rate upstream from the reservoir (backwater zone), and a decrease of actual transport rate below the dam. While aggradation takes place in the backwater zone, the "starved" stream picks up material from the bed downstream from the dam to satisfy the equilibrium requirement.

Vanoni et al. (1961) roughly categorized river engineering problems caused by nonuniform sediment transport. When the actual transport rate is larger than the equilibrium rate (deposition), the following occur:

1. Aggradation upstream from a reservoir.
2. Sedimentation in reservoirs and lakes.
3. Tributary channels bring heavy sediment loads to the main channel, causing local aggradation (examples are fan formation and tributary bar) (fig. 5).
4. Canyon streams discharge on alluvial fans, causing widespread deposition (as in Los Angeles area).
5. Desilting works at water intakes that return all sediment load to the main channel, in which flow of water is depleted, lead to aggradation (e.g., Im-

Figure 5.—A tributary contributed heavy sediment loads to Sycamore Creek, northeast of Phoenix, Ariz. These loads could not be carried by the main stream, and an alluvial fan developed, pushing the flow into the opposite bank. Sycamore Creek flows from right to left.

perial Dam). Remaining flow magnitudes provided a small equilibrium transport rate compared with the original flow.

6. Where river regulation eliminates floods that formerly cleared the channel of accumulated sediment and vegetation periodically, aggradation results in the clogged channel (e.g., Colorado River at Needles).

When the actual transport rate is smaller than the equilibrium rate (scour), the following occur:

1. Degradation downstream from dams that trap sediment and thus decrease the actual transport rate.
2. Canals receiving clear water will scour if the bed material is fine enough that it can be picked up readily by the flow. Under such conditions, the equilibrium transport rate is large, while the actual transport rate of the flow entering the canal is essentially zero.
3. Channel realignments that increase the slope also increase the equilibrium transport rate because of increased flow velocities.

Interdependency of Hydraulic Variables

The complexity of hydraulic variables is immense. Lane (1957) singled out eight variables of this complex which he called most important: (1) stream discharge, (2) longitudinal slope, (3) sediment load, (4) resistance of banks and bed to movement of flowing water, (5) vegetation, (6) temperature, (7) geology, and (8) works of humans. The interrelationships among longitudinal profile, sediment load, and resistance of the banks and bed to movement are particularly close and complex.

Interdependency between many variables often precludes the establishment of one-value relationships. For example, Brooks (1958) found neither the velocity nor the sediment discharge concentration could be expressed as a single-valued function of the bed shear stress, or any combination of depth and slope, or hydraulic radius and slope. He showed experimentally that flow with a given depth and slope can occur with at least two velocities. This is due to changeable bed configuration which causes large variations in the channel roughness. Thus if one or a combination of the interdependent factors change under the impact of external or internal forces, adjustment of one, some, or all of the components will follow.

It is important to recognize that established relationships between most interdependent variables, except for basic factors such as the shear, are empirical and thus not necessarily applicable for a wide range of conditions. Examples are Blench's (1966) equations based on the concept of the regime theory, originally developed by Lindley (1919) and Lacey (1932) for Indian canals. This theory assumes there exists only one type of cross section for a given stream with a given load. Thus width and depth of the channel are the main parameters in the equations. Attempts to reduce the complex stream situation by empirical relationships between a few variables are still pursued (Osterkamp 1977). Obviously, such relationships will be valid only for the area of their origin.

The complexity of the fluvial system suggests stream analysis is a probabilistic problem. Because of the interaction between channel bed, banks, and flow, the core of the problem appears to be the random distribution of the flow energy ($mV^2/2$), where m is the mass of water. The velocity must be recognized as a vector force (i.e., it has direction). Because of turbulent flow in most natural streams, this direction occurs randomly. Thus the energy, itself of stochastic nature, acts on randomly distributed sediment particles. Incipient particle motion is therefore a very complicated event and no satisfactory way of determining it has been found. Sediment transport is a fundamental variable in stream dynamics.

EQUILIBRIUM CONDITION AND ADJUSTMENT PROCESSES

Dynamic Equilibrium

The concept of dynamic equilibrium is very useful in evaluating stream systems and their stage of development. This concept does not imply absolute equilibrium conditions, but that the stream can adjust to a new hydraulic situation within a relatively short time, perhaps within a few years. Obviously, if considered in geologic time spans, dynamic equilibrium has no place, because land denudation is the long-term process. Although dynamic equilibrium cannot be well defined, the investigator can use indicators, some of which are readily recognizable in the channel, to analyze stream stability in terms of equilibrium condition.

Heede (1975) listed several factors indicative of small mountain streams not in dynamic equilibrium: channel headcuts, under-developed drainage nets such as those having channelized water courses only on one-half or less of the watershed area, frequent bedscarps, and the absence of a concave longitudinal profile where watershed conditions are relatively constant. The last condition will depend mainly on geologic homogeneity, availability of bedrock outcrop, and tributaries. When surveying a channel, select a reach with sufficient length to avoid distortion of the overall shape of the longitudinal profile by local irregularities. This length will vary with size of stream. In small mountain streams, lengths of at least 0.25 mile should be sampled in the headwater, middle, and lower reaches. Obviously, greater lengths will improve the representativeness of the profile.

Channel headcuts are local erosion sources because headcuts advance upstream. They indicate that stream length and gradients have not been developed to allow equilibrium condition. Bedscarps that develop at channel nickpoints similarly indicate pronounced breaks

in longitudinal gradients. These scarps proceed upstream until a smooth transition between upstream and downstream gradient is attained. Thus, headcuts and bedscarps substantially add to the sediment load because erosion will be severe until natural channelization is achieved and the longitudinal profile "smoothened." Actual sediment production rates higher than the equilibrium transport rate require steepening of the slope, normally attained by bed aggradation. Since aggradation processes are slow, such a stream must be judged out of dynamic equilibrium because of the long time required for reestablishment of this condition.

Streams in dynamic equilibrium have no headcuts. Their watercourse begins high up on the watershed with a smooth transition from the unchannelized area to the channel. Bedscarps, not developed at locations of rock outcrop or variations in bedrock, are absent or few. As a result, sediment production is negligible. The longitudinal profile is concave. Generally, flow, depth, width, and velocity increase downstream while gradient and sediment particle size decrease if watershed conditions are relatively constant over long stream reaches.

Complex Channel Response

Streams respond to an upset of a given equilibrium condition by different adjustment processes. These processes follow a sequence if considered in terms of relative time and energy expenditures. Channel adjustments, ordered from small to large energy requirements, involve changes in: bed form, bed armor, width, pattern (alignment), and longitudinal profile.

Generally, bed form changes require the least amount of energy and time. Examples of bed forms are dunes in sand bed or gravel bars in boulder-strewn streams. Bed forms determine resistance to flow (bed roughness) (Simons and Richardson 1966). Thus their change (i.e., from a dune to an anti-dune) may be sufficient to achieve adjustment. A dune is a sand wave of approximately triangular cross section in the direction of flow. It has a gentle upstream slope and a steep downstream slope. The dune travels downstream by the upward movement of the sediment on the upstream slope and the deposition of it on the downstream slope.

An antidune is a sand wave, indicated by a regular undulating water-surface wave. Usually, antidunes and accompanying surface waves occur in trains of 3 to 20 or more. If the antidunes move at all, it is upstream. The surface waves become gradually steeper on their upstream sides until they break like a surf and disappear. Often they reform after disappearing.

Where a change in form roughness is not sufficient or is impossible, additional or different processes will be required to attain a new equilibrium condition. An additional process may be armor plating of the bed. It will require more time than bed form change.

If armoring is not possible because of grain size distribution or insufficient amounts of large material, channel width changes generally would be the next adjustment process. Width increases signify increases in the wetted perimeter of the flow, leading to larger roughness of flow and smaller flow velocities. As a consequence, available energies are decreased.

Even width changes may not bring about the required adjustment. The next most energy- and time-consuming process would be channel pattern change to meander or braiding. If topographic and hydraulic conditions do not allow this change, as will be discussed in a later section, bed profile alterations will begin. Generally, these demand the greatest energy expenditures as well as the longest time of all adjustment processes.

Geology, soils, and vegetation also enter into the selective adjustment processes because of their influence on bank and bed stability and hence on sediment transport. Thus they add to the complexity of stream response. One must realize, therefore, an orderly succession of processes, as outlined, may not operate in streams seeking new equilibrium conditions; the most energy-intensive process could be operating by itself. In short, the purpose of the above discussion is to show relative energy and time expenditures between different adjustment responses.

MAJOR ADJUSTMENT PROCESSES

Management activities may trigger or change channel adjustment processes. It is important, therefore, to recognize the adjustment criteria and factors which must be addressed when evaluating management activities in terms of impact on streams.

Five major channel adjustments were outlined in terms of required energy expenditures in the preceding section. The processes responsible for those adjustments are sometimes grouped into two categories: one affecting channel pattern and shape, the other affecting the longitudinal profile. Channel pattern refers to the plan view of a stream and its alignment, while channel shape relates to the cross-sectional view across the channel.

Some processes are reponsible for more than one type of adjustment, however. Thus, bar formation processes may bring about three types of adjustment: in pattern, shape, and longitudinal profile. In a straight reach, for example, alternate bars force the thalweg (line of maximum depth) into a meander pattern. This, in turn, leads to increased stream length and longitudinal profile changes, as well as to changes of the channel cross section. It is also obvious that aggradation or degradation processes change not only the stream's longitudinal profile but also its cross sections. The division of the processes into two categories is therefore a shortcoming of most of our classification systems, but it is accepted for convenience. The relationship between one process and multiple forms demonstrates again the complexity of stream systems.

Four processes affecting channel pattern and shape are recognized. They lead to bar formation, channel patterns, cross-sectional channel shapes, and types of banks.

Different types of bars develop in natural streams. All are integrated into the stream hydraulics and are therefore not necessarily stationary, since most streams change their flows with season and individual events. Each type occurs in a given situation, and hence is an indicator of prevailing flow and channel conditions, as will be discussed in the following section.

Channel patterns are very diversified, as are most products of nature. Three dominant patterns will be described—straight, meandering, and braided—and, as much as known, their causative processes. Straight channels generally offer least problems for land management, but unfortunately, they are the exception. The rule is the meandering channel. Channel alignment changes offer relatively quick and drastic adjustments to a new situation and are easily recognizable indicators of past, present, and possibly future channel developments.

Generally, channel shapes respond quickly to changes in the fluvial system because shape influences water as well as sediment transport. Thus, channels closest to a semicircular shape are most efficient for conveyance of water and fine sediment. Coarse sediment requires relatively wide, shallow channels (Leopold and Maddock 1953). Unstable channels may therefore be recognized by channel shape changes. Parameters have been developed which permit quantitative determination of these changes.

Consistency of bank material and availability of bank vegetation exert a strong influence on channel shape. Besides these factors, water movement within or over banks may play an important role in the attainment of bank stability and shape. But bank characteristics also influence channel patterns. For example, banks of cohesive material (clay and silt, mainly) usually preclude braided stream patterns, but noncohesive materials favor them. Bank characteristics may change due to lateral stream movements. Recognition of these changes is important because they may indicate future bank stability conditions and channel shape. Banks are therefore considered separately from shape.

Older geologic literature overemphasized the importance of the profile in channel adjustment. As shown by the preceding section and stated by Wolman (1955), slope is not necessarily the primary mechanism by which equilibrium is maintained.

Three major processes lead directly to adjustment of the longitudinal profile: (1) aggradation, (2) degradation, and (3) armoring. These processes act on the topography and the material in bed and banks. General relationships between profile, topography, and geology can be utilized to human advantage. An example is the use of a bedrock outcrop for gradient stabilization instead of a check dam.

Generally, aggradation and degradation processes are undesirable, but necessary, adjustments where there are drastic differences between the sediment-carrying capacity of a flow and the sediment load coming into a channel reach. Aggradation may lead to channel widening and flooding; degradation to bank caving and lowering of the water table in areas close to the channel. Armoring can stop the degradation process if sufficiently large bed material is available. In this sense, armoring is a beneficial byproduct of degradation. Amount and depth of the armor material below channel bottom determine the depth of degradation before an effective armor is established.

Processes Affecting Channel Pattern and Shape

Bar Formations

Bars are defined as bed forms having lengths of the same order as the channel width or greater, and heights comparable to the mean depth of the generating flow (American Society of Civil Engineers 1966). Bars are deposits that may be visible or submerged, and of grain sizes ranging from clay to boulders. Most are built predominantly from sand or gravel or both. In longitudinal section, bars are approximately triangular. The upstream slopes are very long and gentle, while the downstream slopes are short and approximately the angle of repose of the bed material. Since bars are an active part of the geometry of flow, they change in size, height, or location with flow conditions.

Generally, bar surfaces rise and fall with the magnitude of flow. Bars generated by high flows frequently appear as small islands during low flows. On sandbars, portions of the upstream slopes are often covered with ripples or dunes.

Bars may be classified as point, alternating, transverse, middle, or tributary bars. The most obvious one may be the point bar, which develops near the convex (inside) bank of channel bends (fig. 6). Its shape may vary with changing flow conditions, but it does not move relative to the bend. The processes leading to this bar formation demonstrate the strong relationship between flow and bed forms. Rzhanitsyn (1960) describing the processes in bends, stresses not only the longitudinal currents but also the cross currents that influence the channel-forming processes. The actions of both lead toward the development of a deep pool at the concave (outside) bank and a bar at the convex bank (fig. 7).

Two causes were thought to be responsible for the transverse circulation: the centrifugal force acting on the particles passing the curve and the difference in the longitudinal component resulting in a general spiral-like motion. The secondary circulation, sometimes also called helical, helicoidal, or spiral flow or current, continually sweeps sediment from the pool depression toward the convex bank, bringing clearer water from the upper layers to the bottom and thus increasing the erosional activity. Most of the material eroded from the pool is deposited on the point bar. These processes lead to asymmetrical cross sections in

bends. Upstream and downstream ends of the bar are pointed. Intensity of erosion increases with increasing secondary circulation. Since this circulation increases with decreasing radius of curvature, the depth of the pool is inversely related to the radius of curvature of the bend. Therefore, gentle bends will have shallower pools than sharp bends (fig. 7).

The maximum depth at the concave bank is greater than that of the straight reach. With the deepening of the channel at the concave bank and the reduction of depth at the convex bank, the principal flow gradually moves closer to the concave bank. There the longitudinal velocity of flow increases due to greater depth. In contrast, the longitudinal velocity at the convex bank is reduced with decrease of depth.

High flows tend to shorten the thalweg (i.e., the flow selects the shortest route as it cuts across the point bar). This process leads to erosion at that part of the point bar located toward the center of the channel. The bar becomes narrower (fig. 6) until other flows may build it up again. Point bars can also be fully submerged resulting in loss of bar height, or a high-flow channel may be cut through the point bar (fig. 8).

Although helical flow apparently plays an important role in the process of erosion and deposition in a bend, the mechanics of bend formation are not known. Meanders are known to form on the surface of glaciers where they are cut by meltwater carrying no sediment load, and point bars do not form. Meanders are also known to exist in ocean currents such as the Gulf Stream where boundaries and loads are absent. Leopold and Wolman (1960) argued, therefore, that the shapes of curves in streams are primarily determined by the dynamics of flow rather than by the sediment they carry. These authors compiled evidence that when other conditions, as yet unknown, cause a stream of any size flowing in a deformable channel to develop a meander pattern, the radius of curvature will be between two and three times the mean channel width.

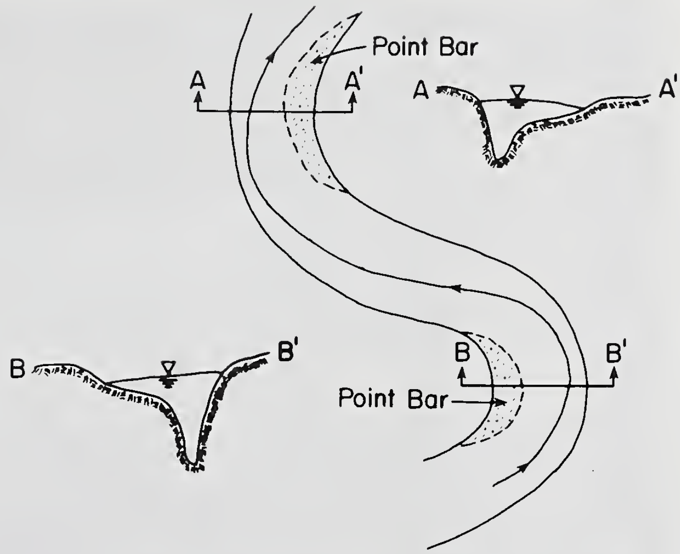


Figure 7.—Schematic presentation of channel shapes in gentle (A-A′) and sharp bends B-B′). The line in the channel of the plan view represents the thalweg. Note in the section view the increase of pool depth with decreasing radius of curvature and the higher water surface elevation at the outside as compared with the inside bank. This is due to the gravitational force and is called superelevation.

In contrast to point bars, alternating bars are not stationary. While point bars form in channel bends,

Figure 6.—Point bar in Salt River north of Phoenix, Ariz. Flow is from left to right in the foreground. Note the pointed downstream bar end.

Figure 8.—In Black Canyon Creek, northern Arizona, high flows cut a channel behind this point bar to speed up water conveyance through this stream reach. Flow is from left to right.

alternating bars develop in straight channel reaches, and are the reason why natural streams rarely remain straight. They "tend to be distributed periodically along a channel, with alternate bars near opposite channel banks. Their lateral extent is significantly less than the channel width. Alternating bars move slowly downstream" (American Society of Civil Engineers 1966). The thalweg meanders between these bars, creating an undulating profile by forming pools and riffles (figs. 9 and 10).

Alternating bars may not be visible because they are often partially submerged. Pools and riffles are spaced more or less regularly at a repeating distance equal to five to seven widths of the channel (Leopold et al. 1964). Because the spacing is similar to that of bends in

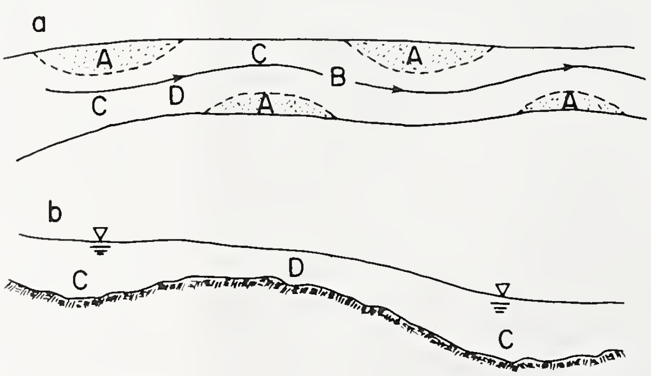


Figure 9.—(a) Schematic plan view of alternating bars (A) and thalweg (B) in a straight channel reach, and section view of the associated longitudinal profile (b) showing pool (C) and riffle formations (D). Riffles form at crossings of the thalweg between bends.

meandering streams, these authors suggest the pool-and-riffle mechanism in straight channels is the same as that creating meandering channels, possibly associated with some wave phenomenon. Normally, the bed material on the riffles tends to be somewhat larger than in the pools, but at high flows, the reverse may exist.

Alternating pools and riffles were not found in high mountain streams of the Sangre de Christos, New Mexico (Miller 1958), nor the Rocky Mountains, Colorado, or the White Mountains, Arizona (Heede 1975). Miller argued the coarse material, left by Pleistocene glaciers or deposited by steep cliffs, etc., is too large to be effectively transported by the present-day flow regime. In Heede's streams, gravel bars were not spaced at a repeating distance, but distance decreased with increasing channel gradient (fig. 11).

Heede's gravel bars could adjust their height with flow while remaining stationary; transverse bars of rivers move slowly downstream and occur both as isolated and as periodic forms along a channel. Generally, they occupy nearly full channel width (fig. 12). Transverse bars result from slope adjustment processes. Their main effect on the flow is increased bed roughness, as shown by strong relationships between bed form and resistance to flow (Simons and Richardson 1966).

Where the width-depth ratio is very large and the stream divides itself into two or several branches to adjust for lost depth, middle bars will be created. At times, they appear as submerged islands. Some are sufficiently long to bear willows (fig. 13). Middle bars are a typical bed form for braiding streams, characterized by extremely wide and shallow channels and flows

passing through a number of small, interlaced channels separated by bars (Friedkin 1945).

Tributary bars often form immediately downstream from tributary junctions (fig. 14). They indicate large sediment discharge from the tributary stream. At times, this discharge may outweigh the capability of the main stream to transport the additional load. A sediment fan may be built at the tributary mouth into the main stream (fig. 5). During a subsequent large flow of the main-stem river, the sediment fan may be fully or partially removed, and only a tributary bar may remain.

Bars are an integral part of the hydraulic geometry of a stream. With the diminution or exhaustion of flood plains and river terraces by gravel quarrying, the streams themselves become increasingly attractive gravel sources (fig. 15). If bars are destroyed by natural adjustment processes, they will not form again unless the hydraulic geometry changes back to the original condition. In contrast, bars obliterated by man will be reestablished if a sufficient sediment supply is available. If not, or if reestablishment is very slow, adjustments such as degradation may take place. Degradation is generally detrimental to the environment. Where transverse bars (bed forms created for slope adjustment) are removed, bedscarps will soon signify degradation is taking place. Removal of sediment will invariably destroy the bed armor, and a new armor can only be established by lowering the bed, which often leads to bank instability.

Figure 10.—Alternating bars (arrows) in Black Canyon Creek. High flows cut small channels through the bars. Flow is toward background.

Figure 11.—Looking upstream on a transverse gravel bar (between arrows) in a small mountain stream (North Fork of Thomas Creek, Arizona White Mountains). Note the steep slope gradient (average 17%) that required adjustment of slope. Consequently, several transverse bars developed above the indicated bar.

Gravel operations may not be harmful where large sediment loads are available to replace bars quickly, thus avoiding drastic upsets of the stream system. The Eel River in California, one of the largest known sediment carriers in the United States, may be such a stream. But even in this case, we would not know the long-term environmental effects (redwood trees have lived for more than a thousand years on the periodically aggrading Eel River flood plain, as shown by multilayered root systems (Stone et al. 1972)).

Channel Patterns

In light of the interdependency of many hydraulic variables, it is not surprising to find a large variety of

Figure 12.—Downstream view of a transverse bar (between arrows) in the Verde River, Arizona. The bar is not fully exposed across the channel. Darkness of the water surface in the two bar openings (A and B) suggests submergence of the bar at these locations. Sediment accumulations above this bar, a natural slope adjustment structure, are indicated by shallow flow depth in the foreground.

Figure 13.—Middle bars (arrows) in the Salt River near Roosevelt Reservoir bear vegetation such as willow and saltcedar. Flow is from left to right. At high water stages, the bars are submerged, while at lower stages, shown in figure, stream braiding develops.

Figure 14.—Where the Salt River (a) is joined by tributary Verde River (b), a tributary bar (c) has formed. Size of tributary bars changes readily if sediment loads delivered by the tributary fluctuate strongly. The submerged outline of the bar at (c) suggests exposed bar size was reduced considerably by recession flows after the heavy load-carrying floods of 1978 and January 1979.

Figure 15.—Many rivers have a substantial supply of aggregates, demonstrated by a large middle bar in the Verde River, central Arizona, that may be sought by industry. In many situations, however, removal of such material would detrimentally affect stream equilibrium.

channel patterns because pattern changes are one possibility for adjustment of the hydraulic geometry to a new situation. This is especially true if the slope must change. The large variety of patterns can be reduced to three basic types: straight, meandering, and braiding. There are, of course, intermediate forms.

Long reaches of straight channels are hard to find in nature. Even in straight channels, the thalweg wanders back and forth between the banks (fig. 10), and only the high flow may fill the straight reach. One could thus conclude that meandering and braiding channels offer better and easier ways for attaining equilibrium conditions than straight channels. Meandering and braiding increase the length of the thalweg and thus decrease slope. A measure of meander intensity is sinuosity, expressed as the coefficient of thalweg length divided by valley length. Large coefficients, therefore, express strong sinuosity (meandering). A straight reach would have a coefficient of 1.

In braided streams, the flow is relatively shallow and the width-depth ratio large, larger than in meandering streams. The stream flows around many islands (fig. 16). If this process increases, branching of the main channel may occur, the flow running in different channels more or less parallel to each other, joining and anabranching (diverging) in succession. Brice (1975) called these "anabranching streams."

Why channel patterns change cannot be precisely answered yet. Certainly, localized channel width increases may lead to meandering because of introduced flow deflections. A large boulder or other obstruction, for example, may cause a local channel width increase that results in a meander. But on glaciers meanders also appear without visible flow deflections.

Profile is one of the major causes for pattern changes. Braided streams are steeper than meandering streams. Steeper streams have higher velocities, attack banks more strongly, and carry larger sediment loads.

For bank erosion to occur, erodible bank material must be available. For example, braiding does not usually take place where banks are densely vegetated, but may where this cover is sparse. Although cause and effect are suggestive, they are not proven (Leopold et al. 1964).

In alluvial streams, whose bed and banks are formed by sediment transported by them, amount and character of the particles composing the sediment load also seem to have an important effect on channel pattern. It appears available load is one of the factors separating meandering from braided streams. Lane (1957) concluded not only overloading by sediment but also steep slopes are prerequisite for braiding. Overloading leads to aggradation, causing wide channels where banks are soft and, thus, the development of bars and islands. The width-depth ratio is larger than in meandering streams. But Leopold et al. (1964) pointed out that braiding is not necessarily associated with aggradation, since it can represent the equilibrium pattern (sediment inflow equals sediment outflow). Yet it can be argued that for braiding to occur depositions (aggradation) are required to initiate drastic channel width increases; with braiding, a new equilibrium condition may be established.

In flume experiments, Shen and Vedula (1969) showed depth of flow may become so shallow due to sediment overloading that flow could not occur in a single channel. It had to divide into several narrow channels to increase depth of flow and sediment-carrying capacity.

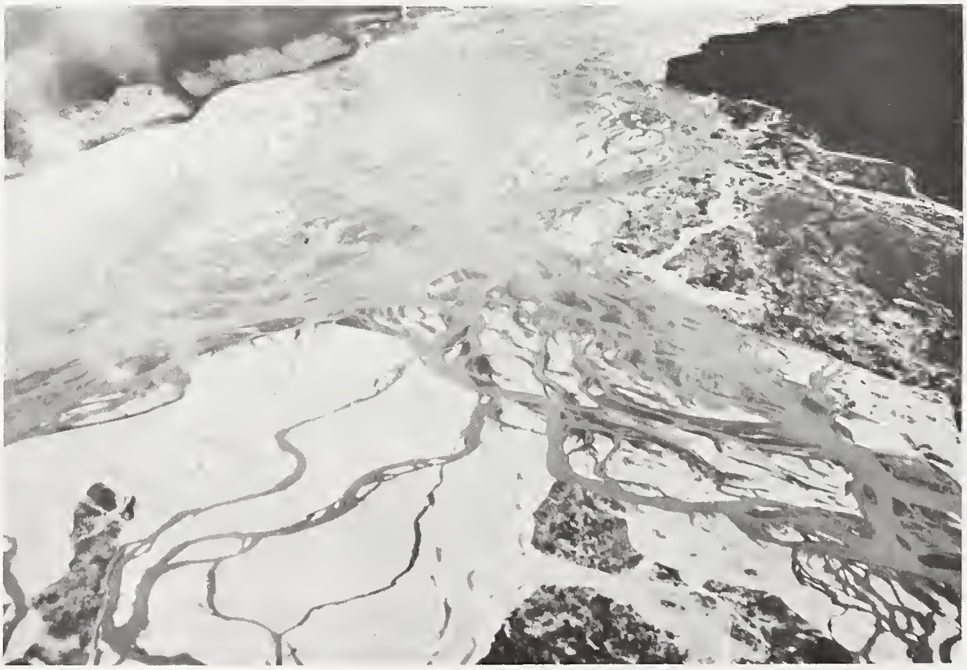


Figure 16.—Looking downstream on Delta River, a braided glacial stream draining the north face of the Alaska Range in central Alaska. Glacial streams tend to develop very pronounced braided patterns. (Courtesy Troy L. Péwé, Arizona State University)

Figure 17.—Heavy sediment loads in this Salt River reach above Roosevelt Reservoir, Arizona, created a wide bed with shallow flow depth. Thus, stream competence (sediment-carrying capacity) was drastically reduced. To increase flow depth (and competence), the flow split into several channels (arrows). Flow in the foreground is from left to right.

That this process takes place also in rivers was demonstrated during a recent recession stage of the Salt River, Arizona (fig. 17).

In a glacial stream on Mount Rainier, Washington, Fahnestock (1963) observed braiding at much greater magnitude when an abundant bedload was introduced than when the material was derived just from bank erosion. Fluctuating flow discharges also favored braiding.

In some situations such as mountain streams flowing in V-shaped valley bottoms, lateral stream movements are not possible. A straight channel reach may therefore remain straight. Slope adjustment is possible only within the given channel. In small streams, this adjustment may be achieved by the formation of transverse gravel bars (fig. 11) and incorporation of fallen trees and logs (Heede 1975). Apparently, slope is seldom adjusted by severe degradation because of the presence of large bed material sizes.

The limitations set by the topography, such as V-shaped valleys, help to explain why braids tend to develop in channels having certain variable combinations, while meanders occur in different conditions; the straight pattern can occur in either.

Although causes for pattern changes cannot be precisely delineated (Morisawa 1968), channel changes obviously take place in response to changed stream conditions. For the land manager, meander and braiding processes are usually costly because valuable land may erode or other investments, such as roads or buildings, may be destroyed. It is therefore desirable to control lateral stream movement, but vertical bed adjustment processes may be initiated if the lateral process is stopped. Unless durable bed armor prevents channel depth changes or these changes are acceptable, additional bed control measures will be required. If depth changes are permissible, it should be recognized bed adjustment will also take place in the tributary streams. Thus a stream control measure may have adverse effects far beyond the immediate region of the stream.

As a general rule, the land manager should live with the present natural adjustment processes and, if possible, offset losses with land improvements elsewhere.

Channel Shapes

Channel shape is of management interest because shape is predominantly influenced by the (1) quantity of water; (2) the type of sediment load (suspended load, the material moving in suspension; or bedload, the coarse material moving on or near the bed); and (3) the type of bank material. Any change in one or more of these factors will therefore introduce a shape change as well. Recognition of shape changes is a first step in the determination of their cause, but recognition is not always easy because of turbidity of the water, or transitional shape changes that are not easily seen (for instance, from slightly parabolic to rectangular). For these cases, the width-depth ratio and the shape factor can be calculated from field survey notes on channel cross sections. Both will be described in succeeding sections.

Land management measures can influence water and sediment discharge. Costly stream training measures such as riprap or gabions change banks and

their material makeup. Such changes may be beneficial or detrimental to management goals. For example, a semicircular cross section, not existing in natural streams, would convey the largest quantity of water with the least resistance (erosion or deposition). The more channels deviate from this idealistic shape, the less water will be conveyed, and flow resistance increases. Thus a wide flat channel will show tendencies for aggradation by sediment, possibly leading to a braided channel pattern. Obviously, granting permission for additional water conveyance through such a channel would add to the problem.

Relations between shape and sediment load show channel width increases with increasing coarseness of the sediment particles. Thus, causes for channel widening may be traced back to new sediment sources on the watershed caused by events such as landslides or rockfalls from talus (cliff debris) slopes, or channel deepening in an upstream reach may make available coarser material. Of course, the basic question of what caused slides or deep cutting must still be answered before corrective management actions can be initiated.

Also, the particle sizes in the channel banks determine channel shape. While banks with a high silt-clay percentage lead to narrow and deep channels, those with a predominance of sand and coarser material develop into wide, flat channels. Thus, lateral stream movements may lead to shape changes by exposing different bank materials.

Lateral stream movement may not be caused by management but may result from natural adjustment processes where dynamic equilibrium was lost due to unusual events such as earthquakes or land flows (unusually large land slides). If bank material changes are detected at an early stage and future problems are expected, protective actions could be taken in time. For such a decision, projections must be made as to other types of adjustment the stream may undergo if lateral movement is stopped. Down cutting may take place, for example, requiring additional bed control structures under expected severe conditions.

Width-depth ratio.—The width-depth ratio relates the top width (*W*) of the channel to the mean depth (*d*). Mean depth is defined as the cross sectional area at bank-full stage divided by the top width. Where bank-full stage would not be a meaningful criterion, channel width and flow depth should be taken at high water mark. In cross sections with nongeometric forms, a planimeter or similar instrument is best suited for determining cross-sectional area.

In cross sections with pure geometric shapes, the following relationships hold: in a triangular channel, the width-depth ratio remains constant with changing discharge; the width-depth ratio decreases in trapezoidal and elliptical cross sections when discharge increases; and width-depth ratio decreases much more rapidly with increasing discharge in rectangular channels.

Width-depth ratio changes with discharge can be graphically shown if the ratio is expressed as a simple power function of discharge:

$$w/d = rQ^s$$

where Q is the discharge, and r and s are numerical coefficients. The value of s, the slope of the line resulting from a log-log plot of the equation, expresses the relative rate of decrease of the ratio with increasing discharge (i.e., it constitutes a measure of how readily a stream adjusts width and depth to discharge changes). An example from three stations is plotted in figure 18.

In general, cross sections in straight reaches have a large width-depth ratio. In bends, this ratio is small. The sharper the bend, the deeper the pool, and the smaller the ratio (fig. 7). This relationship is so strong the cross-sectional shape of the pool could be used to determine the approximate degree of curvature of the bend if empirical data on bends and bank material are available.

Schumm (1960) found that in western channels the type of material in banks and bottoms controls the cross-sectional channel shape. When the mechanical analysis of the soils was related to the width-depth ratio, linear regression indicated that increases in the ratio conformed with the increases of the average percent sand in the measured load: wide, shallow channels form in sandy soils, while clayey soils lead to narrow, deep channels.

An extremely large width-depth ratio for a given river would indicate braiding must be expected because of large available loads and unstable banks or very large width of channel. The decreased flow will concentrate into smaller branches to obtain some depth and velocity for the transport of the material. Values for the ratio should be evaluated relative to prevailing values within the stream system. The range of the ratio can be large. Fahnestock (1963) found values ranging from 10 to 71 for glacial streams of Mount Rainier in Washington, while those for small streams in the southern Rocky Mountains of Colorado ranged between 3 and 27 (Heede 1972).

Shape factor.—The shape factor is the quotient of maximum depth divided by mean depth. Because the value may be the same for a variety of unusual cross sections, the factor must be interpreted cautiously. Only in exceptional cases, however, do channels in alluvial material have unusual sections. If considered as geometric figures, a triangular channel has a shape factor of 2, a parabolic section 1.5, and a rectangular section 1.0.

As stated before, the semicircular channel would have the most efficient cross section, because for a given cross-sectional area it has the smallest wetted perimeter. If slope and roughness are constant, the velocity increases with the hydraulic radius, which is the coefficient of area of flow over wetted perimeter. Hence, the semicircular channel would discharge more

water than any other channel shape. The most efficient naturally occurring cross section is a parabolic channel with a shape factor of 1.5. Thus, the discharge efficiency of a channel can be quantitatively judged. This may be of importance for projects which require additional conveyance of water. Where cross sections appear to be obscure, plotting the section will reveal if the factor truly expresses the shape. In the streams mentioned above, Fahnestock's (1963) shape factors ranged from 1.1 to 2.7 and Heede's (1972) ranged from 1.1 to 2.3.

Avoiding pitfalls in "in-stream flow" investigations.— Surveys of channel cross sections are an integral part of the land manager's "in-stream flow" investigations. The present type of flow should be defined because, as shown in a previous section, with flow the thalweg may

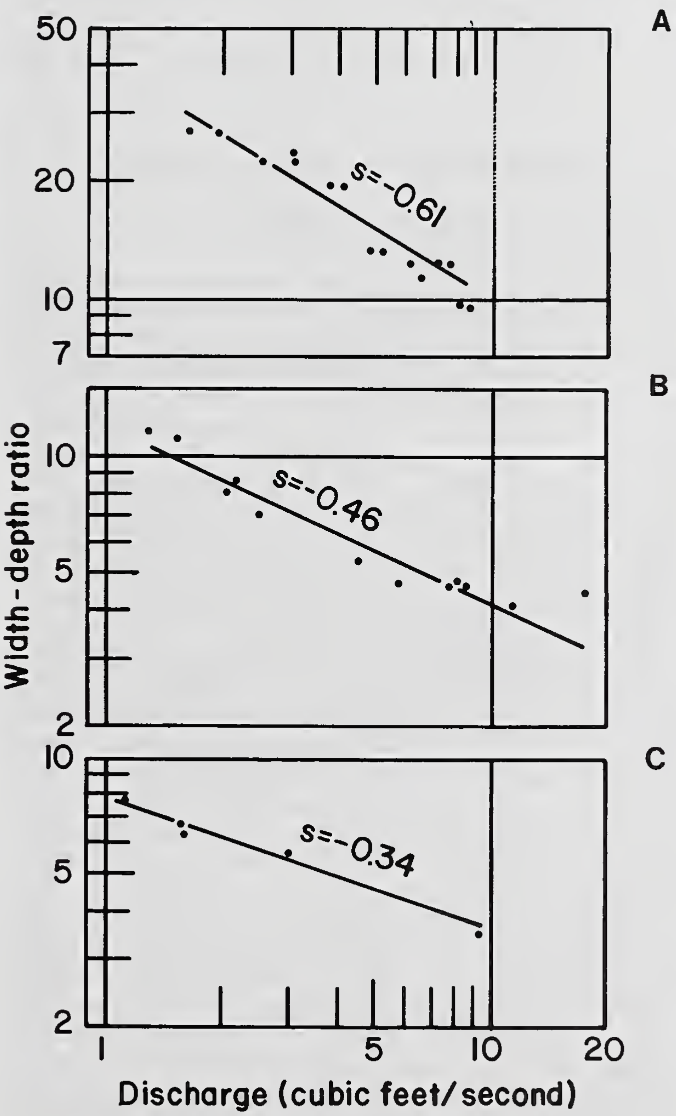


Figure 18.—Relationship of width-depth ratio to discharge for three stream stations of Fool Creek, central Rocky Mountains in Colorado. Station A adjusted most quickly to discharge changes (sediment carrying capacity is better maintained in A than in B or C).

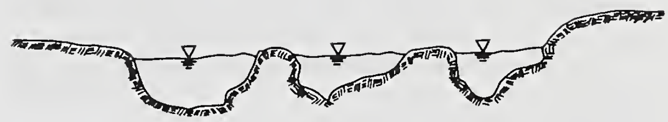


Figure 19.—Schematic diagram of a channel cross section in an anabranching river. The overall appearance suggests several independent parallel streams.

change its position and in turn channel shape. At low flow, for example, the stream may create a pool at a bank due to increased flow sinuosity; while at high flow, water fills the channel and a low occurs in the section center.

How flow types can influence channel shapes is determined not only by the thalweg position in the cross section, but also by changes of the stream power. The cross sectional channel shape is directly related to the changes of the stream power τV across the stream, where τ is the tractive force γRS; γ represents the specific weight of water, R is the hydraulic radius A/p, A represents the area of flow, p is the wetted perimeter, and S is the slope. The wetted perimeter is that part of the channel cross section submerged under the water of a given flow. Simons and Richardson (1966) have shown τV is related to mean sediment grain size, which determines bedform and, in turn, resistance to flow.

Cross sections can be influenced also by channel patterns. Thus a straight reach tends to have a V-shaped cross section; in bends, a pool exists at the outside bank (fig. 7); while in braided streams the cross section has an undulating outline. Where anabranching takes place, a given stream location may have a succession of channel cross sections each separated from the next by unchannelized sections (fig. 19). The survey should therefore include information on the channel pattern and the location of the section relative to pattern features such as "at crossover between meanders." This information is important because the pattern itself may be responsible for a given type of flow and channel shape, and different processes induced by different patterns may form similar cross sectional shapes. Examples will illustrate this.

In a straight reach, two circulation cells have been observed in the plane perpendicular to the flow (Leopold et al. 1964). The authors presented cross-channel water-surface profiles showing a marked central hump and water surface elevations lower at the two edges of the stream, resulting from the transverse water circulations (fig. 20). This so-called secondary circulation moves from the edges to the stream center and then downward. There may also be several circulations above each other, but circulation seems to take place in an even number of cells (Koloseus 1971). The secondary circulation has been associated with

turbulent flow in prismatic channels illustrating an influence of channel shape on flow characteristics.

At a meander crossing (the point of inflection from one meander to the next), the flow is often deflected towards one bank. This leads to the formation of a pool there and a bar at the opposite bank. Appearance of such a section in a cross-sectional drawing may be similar to that of a meander. Only the plane view would show dissimilarity in appearance.

If instability of flow increases at a meander crossing, a bar may form in the middle of the channel, practically dividing the flow into two branches. At low flow, this may appear like the cross section of a braiding stream. Description of the section location is therefore required. Because of inherent instability, meander crossings should be avoided for structural installations such as bridges and culverts.

Channel Banks

With time, most natural channels form their bed and are therefore embedded in alluvial materials. Banks may offer serious soil mechanical and fluvial geomorphologic problems. Factors such as temperature, chemistry of clay, or vegetation influence bank stability. Bank material may range in size from clay to boulders, and the occurrence of this material may change with location or it may be stratified. Generally, banks with high clay content are more stable than those without clay. Therefore, the bank material must be considered if bank stability is evaluated.

Failures of banks are customarily classified into slip failure and scaling. Scaling is a type of exfoliation that produces thin flakes, laminae, or scales. Slip failures are induced by piping (development of pipe-like subterranean tunnels) or often indirectly by horizontal stratification of the bank materials. Scaling begins in smaller magnitudes at the bank toe, generally, and proceeds up the bank.

Where piping takes place, material stratification may add to the problem. This stratification should be considered relative to high and low flows and to the elevation of the water table in the bank. Piping is subterranean erosion where soil is removed from root canals, cracks, burrows, or other voids in the solum. Normally, pipes have an inlet and outlet, the latter at a lower elevation, and thus convey overland flow. Repeated flows increase tunnel size until it collapses.

Heede (1971) described soil piping in gully banks with high-clay soils (>45% clay), and found piping was related to high exchangeable sodium percentage, low gypsum content, and fine-textured soils with montmorillonite clay.

Vegetation as a bank stability factor must be evaluated in terms of plant vigor, density, and rooting depth. Obviously, the stronger these characteristics, the greater the impact on bank stability. Research results are few on this subject, and the designer can be guided only by experience and judgment.

Where the load of a stream consists of large amounts of fine sediment, extensive berms may form along the banks by deposition of silts and clays. On the other hand, where channels widen continuously, the process must be suspected to be a function of the bank material.

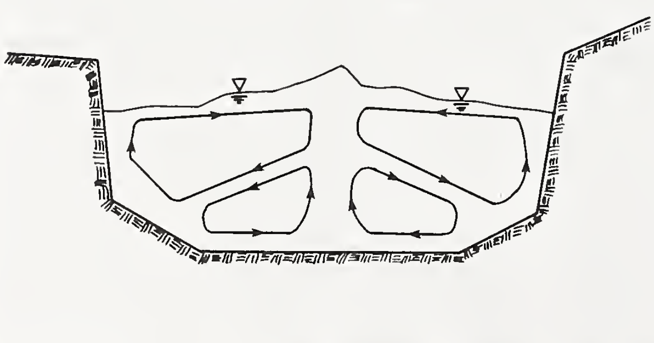


Figure 20.—Idealized secondary circulation cells in a cross section of a straight reach. Water surface elevation shown (Leopold et al. 1964). Note the water surface shows a hump in the channel center and a low at both banks. The central hump may be as much as 1 foot above water surface at banks.

Processes Affecting Longitudinal Profile

Longitudinal Profile Relationships

The longitudinal profile of a stream is determined largely by the topography. In general, stream gradients will decrease from the headwater downstream to the mouth, but gradient steepening or lowering may occur in any stream reach, especially if there are human or natural controls such as rock outcrops or rock type changes. When evaluating the overall shape of the longitudinal profile, one must be aware of the scale factor that may enhance local irregularities and thus misconstrue the overall shape. Profile shapes can be classed as concave, straight, or convex if local irregularities caused by bed features such as bars, pools, and riffles are ignored.

The longitudinal profile is a function of the following variables: discharge, load, size of sediment particles, flow resistance, velocity, width, depth, and slope. Since there are more unknowns than equations, an exact solution incorporating all variables is not possible. Simplified equations of various forms have been devised, however, typified by two kinds. One is based on Sternberg's (1875) abrasion law, the other on Gilbert's (1880) law of declivities.

Langbein (1964) suggested the concavity of river profiles with uniform discharge increases with length and decreases with rate of discharge. He proposed further that profile shape is independent of base level and is determined by length, fall, and discharge. Concavity can be expressed as the ratio $2A'/H$, where A' is the difference in elevation between the profile at mid-distance and the straight line connecting the ends of the profile, and H is the total fall (fig. 21).

In small mountain watersheds with homogeneous geology, Heede (1977) found ephemeral streams with convex profiles, while perennial streams showed con-

cave profiles. He argued, considering homogeneous geology and other parameters of flow and channel geometry, concavity represents the equilibrium profile and convexity represents the profile of streams outside of equilibrium.

Previous sections showed that the processes leading to a given profile are interrelated with others. Together, the processes tend to either establish or maintain equilibrium conditions. Since the profile directly influences flow velocities, artificial changes of the equilibrium slope should be avoided.

Where a stream must share a narrow valley bottom with a road, the stream reach is often shortened, steepening the channel slope. Normally, a bedscarp develops at the downstream end of the shortened reach and proceeds upstream with time, deepening the channel (fig. 22) and the tributaries. The deepening of the main channel lowers the local base level of tributaries to which they must adjust. In many cases, available space does not permit relocating the road in such a way that new channel length equals the original. Artificial armor plating or check dams would solve the problem, but are expensive. Where check dams are used, it is important that the last upstream structure will not create a pronounced break in gradient at the upstream toe of the future dam deposits. A smooth transition from the lower to the upper gradient is required to avoid the development of a bedscarp at the deposition toe. An expected deposition gradient should be estimated from measurements of deposits above artificial barriers within the stream system.

Aggradation

If the sediment inflow into a reach is in excess of the reach's carrying capacity, the excess material is deposited until a new slope is established that equals the upstream slope. This is the new equilibrium slope. Based on flume experiments, Suryanarayana (1969) reported on the mechanics of aggradation. The new equilibrium slope established by aggradation can carry all the incoming sediment, but downstream the slope has not adjusted yet and deposition occurs. This obstructs the flow, and deposition occurs above also. Thus, deposition takes place above and below this

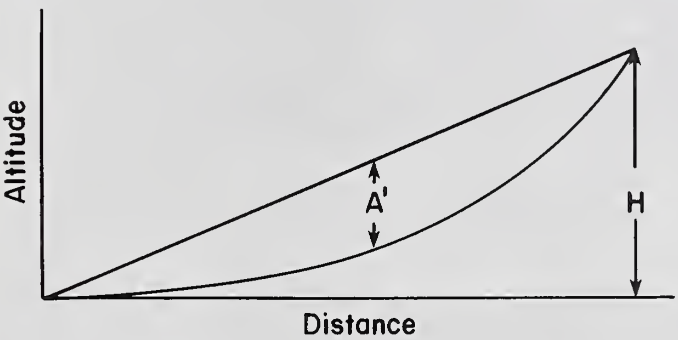


Figure 21.—Schematic illustration of Langbein's (1954) profile concavity ratio.

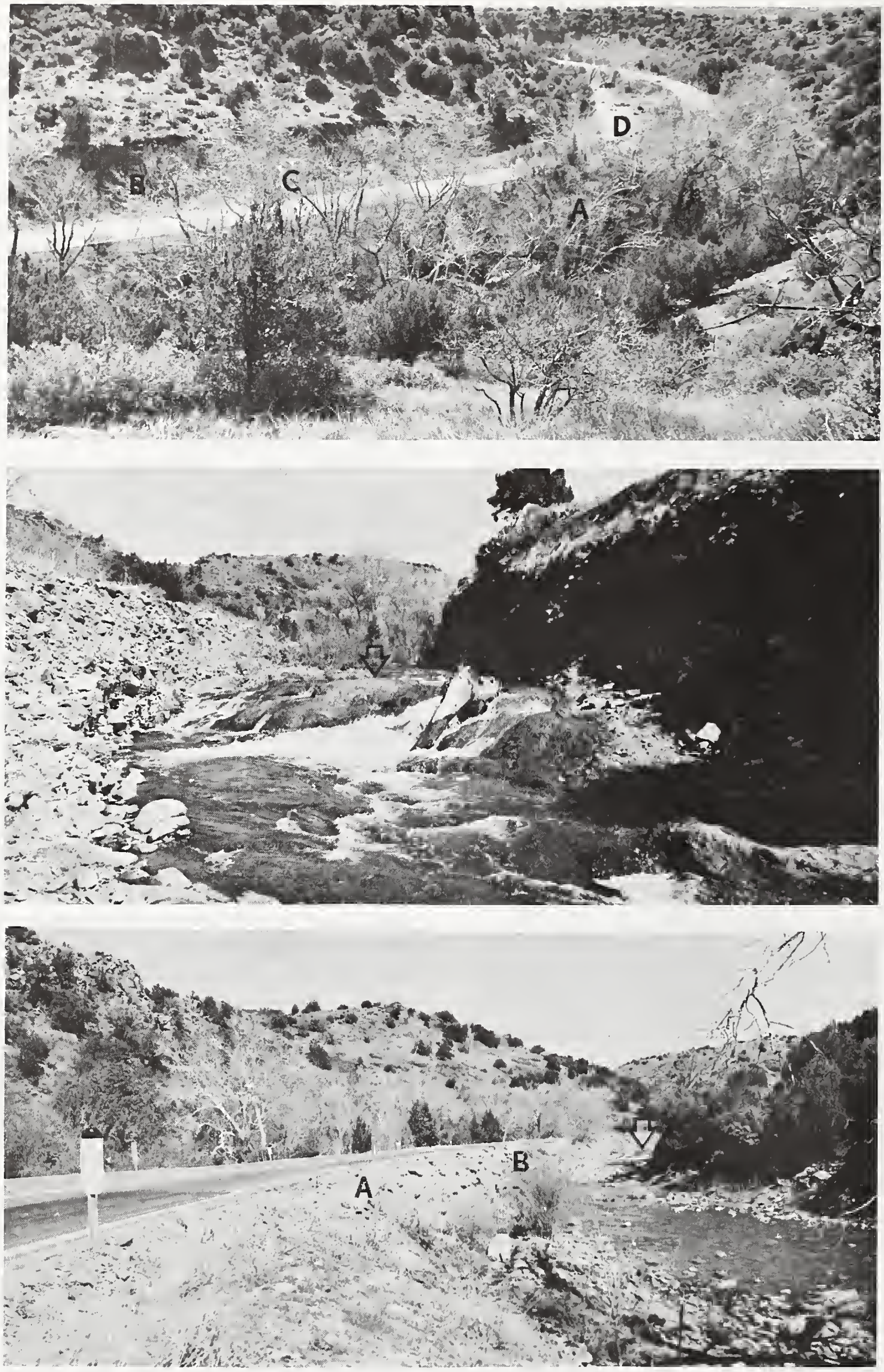
location, raising the bed parallel to the new equilibrium slope. The rate of this movement decreases with time or with downstream advance, and so does the rate of aggradation. The channel upstream and downstream from the aggrading front behave as two different reaches with different flow conditions. Aggradation ceases once all slope segments allow equilibrium sediment discharge.

Aggradation creates a slightly convex longitudinal profile (Suryanarayana 1969) resulting from interaction between transport and deposition. Since more power is required to move coarse material than fine material, the coarser sediment will be deposited first while the fines move farther downstream. Particle sizes of sediment therefore decrease downstream within the aggrading reach. Particle abrasion becomes an additional factor (Schumm and Stevens 1973).

Where aggradation takes place, the streambed rises slowly and, with time, the tendency increases for the flow to spill over the banks. This will lead to rising of the banks. A good example is the Rio Grande at Albuquerque, N. Mex., where the streambed aggraded to an elevation 4 to 6 feet above the river's flood plain. The banks rose, but not high enough to contain exceptional floods and stream training measures were required to safeguard the city.

The process leading to natural levee formation (raised banks) can be explained by sedimentation. When floodwaters spill over banks, a sudden loss of transporting power occurs at the brink of the banks due to decreasing flow depth and flow velocity. Most of the transported sediment is thus deposited at the brink and much less material is available for deposition on the flood plain (fig. 23). Under extreme flooding or bed aggradation, the stream may divide itself by building another channel on the flood-plain side of the levee, and the levee keeps both channels apart. This process may continue during successive floods, and the end result is a "braided" river. This example illustrates an important fact in stream hydraulics: different types of processes may lead to similar end results.

Unfortunately, flume studies are not helpful in predicting the behavior of natural alluvial channels. The main reasons are flumes have rigid boundaries, and sediment characteristics such as shape and smoothness cannot be modeled. Knowledge of natural streams must therefore be developed under field conditions. Yet, due to the intricacy of different adjustment processes in alluvial channels all of which may be acting at one time, we cannot precisely forecast what will happen at any one point. The problem is compounded by the fact individual processes require different time scales. Thus, bed forms may adjust quickly and width slowly or erratically, while the processes leading to longitudinal stream profile changes are slow. The aggradation process is somewhat faster than degradation; the two processes generally alternate along the length of the stream. In short, morphologic adjustment processes are stochastic in nature, and stream behavior prediction is therefore a probabilistic problem.

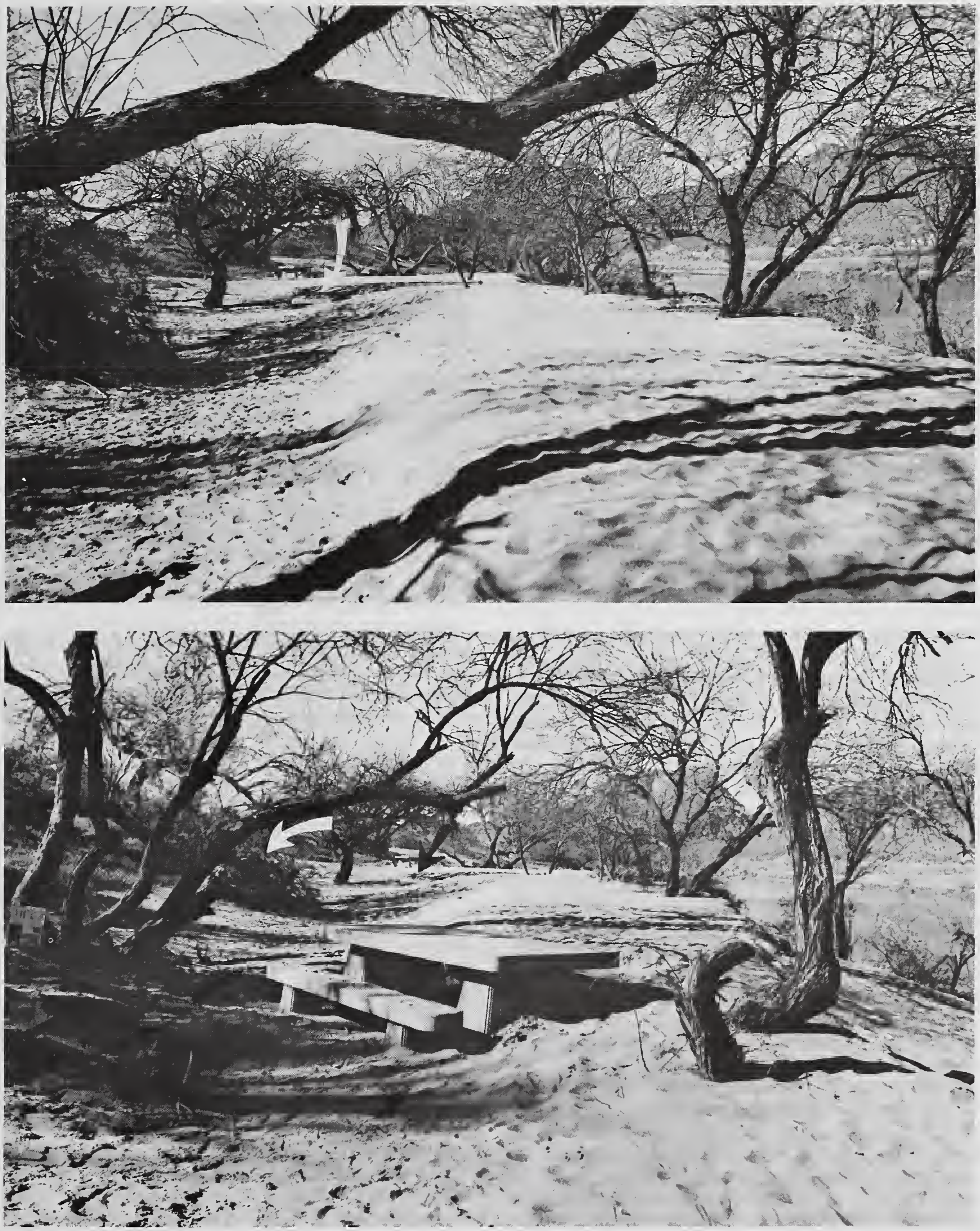


a

b

c

Figure 22.—(a) In mountain country, highway construction often infringes on streams. A relatively large meander bend (A) of Sycamore Creek, central Arizona (flowing from left to right), was cut off and the streambed relocated to the opposite side of the road (B). Thus streamlength was shortened, slope gradient steepened, and a nickpoint introduced at (D) that led to the development of a bedscarp in the volcanic bed rocks. This scarp advanced about 300 feet upstream (C) within approximately 25 years. At (D), the original meander bend connected with a short straight reach still used by the creek. (b) Closeup view of the 8-foot-deep bedscarp (arrow). Adjustment processes not only caused a bedscarp but also tried to reestablish the meander, endangering the road bed by undercutting. (c) Rock riprap bank protection was required between A and B to protect the road. Arrow signifies bedscarp location.



a

b

Figure 23.—(a) A natural levee was formed along this bank of the Salt River, south of the confluence with the Verde River in Arizona. Within 11 months prior to the date of the photograph, three major floods had covered the picnic area indicated by a partially buried table (arrow). Note the cross-sectional dike shape of the levee. The view is downstream. (b) The levee partially buried one picnic table (foreground) and one fully (black arrow). White arrow points to the high-water mark of the January 1979 flood.

Unless an unusual event occurs such as a flood, slow profile adjustments are difficult to observe. Normally, many years of investigation will be required, therefore, to test the effectiveness of a design. Observation reaches should be as long and as uniform as possible so that the average bed conditions are insensitive to seasonal changes (Gessler 1971) that could distort the results.

Degradation

In general, degradation processes are extremely slow, especially where geologic processes such as uplift are involved. A classic example is the Grand Canyon in Arizona.

Where equilibrium conditions have been violently disturbed (massive land slides, earthquakes), degradation may be fast initially, but will become progressively slower with time. An example is Manti Creek, draining the Wasatch monocline in Utah. In 1974, the third largest modern landflow in the United States lifted portions of the streambed by about 110 feet. Within 2 to 3 years, degradation in the uplifted reach amounted to about 60 feet. Degradation is now so slow that downcutting rates cannot yet be established.[2] Manti Creek's behavior, typical for alluvial streams, illustrates that degradation processes are asymptotic in nature and, therefore, slow if considered over the full adjustment time.

The profile of a degrading bed is concave (Suryanarayana 1969), and the associated channel cross sections tend to be V-shaped (Gessler 1971). As for aggradation, the processes shaping the profile of degrading reaches can be described in terms of sediment transport. During degradation, material is picked up from the bed until load limits (threshold values for the transport of particular grain size) are reached. While certain smaller sizes are still set in motion, the larger ones remain in place until even the small sizes cannot be picked up. With the limitation in bed particle movement, the slope of the concave profile decreases downstream. The gentler bed gradient will have an equilibrium sediment transport rate less than that of the upstream degrading reach.

The tendency for formation of V-shaped cross sections in degrading channels is a result of variations in resistance to flow across the channel. Normally, carrying capacity for sediment is lower near banks than in the channel center due to bank roughness. Pickup of bed material may therefore increase toward the center. Other processes, however, such as spiral-like flow in bends (discussed in an earlier section) may have an overriding influence on channel cross-sectional shape. Also, the profile may not be concave if only considered over short distances.

The processes of degradation as well as aggradation are thus correlated with flow and sediment transport. The aim of these processes is to adjust to some change in the stream system; the end result is a new equilibrium condition. Except for adjustment processes that are detrimental to immediate management goals or to important installations, the land manager therefore should not interfere. If possible, he should work with the stream processes, not against them. Such an approach is less costly. For example, dredging the river bottom in aggrading reaches is not always unavoidable, but is nearly always of infinite duration and excessive cost (fig. 24).

Figure 24.—Tractor excavation of sediment from this streambed was unavoidable because of the road location. Since sediment loads are very high during high flows, as indicated by high frequency of large bars in the river, this branch channel will refill. In the long run, relocation of the road may be less costly than repeated excavations.

Armoring

In many situations, the process of degradation is halted by the selective transport of the flow before the equilibrium slope is attained. This slope would have corresponded to the original bed material gradation. An example is Livesey's (1963) report on the Missouri River below Fort Randall, where 15 feet of degradation was expected. But after the bed had lowered 3.5 feet, degradation ceased because an armor was established on the bed. Within 10 years, the D_{65} (65% of the material on the cumulative curve is finer than the size D_{65}) increased from 0.20 mm to nearly 1 m, representing a coarsening of bed particles by 500%.

During the armoring processes, smaller particles are carried away by the flow, while the larger ones remain in place and create a stable bed. Two prerequisites must be fulfilled before an armor can be established: bed material must include a gradation from finer to larger grain sizes (which is true for most natural streams), and fluctuations in flow magnitude must be mild and flow velocities relatively low during time periods long enough for armor formation.

The armor coat is determined by the largest flows of the establishment period because particles light enough and available for transport are moved out by these flows, but by no means are all smaller grain sizes removed, although the large components are predomi-

[2]Oral communication with Manti-LaSal National Forest personnel, and personal site observations.

nant in the armor. The individual larger grains exert a shingle effect by fully or partially covering smaller ones thus keeping them in place (Lane and Carlson 1953). There is no distinct boundary, therefore, between the armor and the sublayer. The armor becomes effective when it is one grain size thick (Lane and Carlson 1953). Future flows, larger than those experienced during the establishment of a given armor, may destroy the present coat and a new armor, consisting of a predominance of still larger particles, may be created. In contrast to the aggradation and degradation processes, armoring does not cause bed slope changes; instead, the bed is lowered parallel to its original slope (Gessler 1970, 1971).

Although precise quantitative projections on armor development are not possible (Little and Mayer 1976), the investigator should attempt to determine the availability of large sediment particles in sufficient quantities which can resist the largest flows in a given time period. Under conditions of degradation, this material must be exposed by a flow before it can act as armor. The size distribution of the sediment buried below the bed layer or in the banks is therefore important. If newly exposed banks are sufficiently soft for alignment changes to take place, degradation will not continue generally.

Where high values are at stake, Gessler's (1967) method of prediction should be used. This requires data on flow and sediment transport, which in many cases must be generated before analysis can proceed. Where the situation permits and data are not available, the expected depth of degradation and armor plating can be estimated by comparing present bed materials with those expected to be exposed by degradation. Drilling or other excavations would be required to determine the size of the lower bed materials. Because the judgment requires experience, an expert should be consulted.

THE NEED TO MONITOR STREAM BEHAVIOR

We should not underestimate the benefits that can be derived from predicting stream behavior. If bridge piers will be undermined by scour (degradation) or the bridge buried by sediments (aggradation), such knowledge is most valuable for management action even if it is not precise in time and volume. But data are required to make sound predictions. Many stream projects have been completed, but post-project behavior is seldom monitored. Monitoring is also needed because most theoretical relationships were developed under controlled laboratory conditions, and verification or modification of the relationships by case histories is required. Observations spanning long stream reaches and long time periods are expensive, but how else can we increase our knowledge about the real world?

Monitoring should be based on sampling at random or predetermined stations to reduce expenditures. Generally, the latter approach is preferable because fewer stations will be required for representation. An example would be the establishment of one sediment sampling station each in the head water, middle, and lower stream reach, since stream gradients and sediment particle sizes generally decrease downstream while flow and velocity increase. Often, average gradients of the reaches can be determined from maps. But sampling of total sediment load, one of the most influential hydraulic variables, is difficult. Bedload can be sampled only in catch basins or where turbulent flow places the total load in suspension. The latter condition may be found where channels are excessively constricted. Thus, usually only suspended load is monitored (by use of dip or pumping samples) to represent sediment load. Often, suspended load is 75% to 90% of the total.

Bed material particle sizes can be sampled at low flow. A grid pattern should be used comprising an area on the bed from bank to bank. Sampling total bed width will ensure the particle changes with changing flow lines across the channel will be representative. Wolman (1954) tested such a pattern and found significant representation of the particle size distribution. Changes in particle sizes are indicative of changes in bedload transport.

Monitoring bed material at a stream-gaging station will not show true sediment production in a watershed because of the lag time between production at a location and transport to the station. Especially in ephemeral streams, many years may pass before a substantial part of the sediment production reaches the station; and some amount never will (Heede 1976). Also, channel storage by bar and other depositional features (bed aggradation, riffles) generally is many times larger than the bedload caught at the gaging station.

If any sediment transport equations are to be used, they should be thoroughly tested for applicability. Because stream behavior involves intricate processes as demonstrated in the preceding sections, the processes have different modes at different flow conditions.

If stream-gaging stations are not available, a current meter or velocity headrod should be used for flow determinations. Heede (1974) showed velocity measurements by the rod require less time. In boulder-strewn streams, results did not differ significantly from the current meter readings.

Where channel cross sections must be sampled because of expected severe consequences from future channel shape changes, it is important to select representative sections of a reach. These can best be determined from aerial photographs, if low-flying images are available, or by ocular selection on the ground.

To facilitate ground surveys, bench marks should be established at some distance from the brink of the stream banks. Regular land survey tools such as a hand level or engineer's level will suffice.

The intensity of stream sampling depends on the objective and on available funds. But if the user focuses on the basic stream processes as outlined in this report, the complexity of stream dynamics can be

better understood and efforts limited to essential monitoring.

CONCLUSIONS

This report focuses on the major processes of stream dynamics and shows how the complexity of stream behavior forces the user to consider the individual components of each case. The report should be helpful in delineating the individual characteristics. Above all, stream restraining measures must be applied with great caution so that treatment of one critical location will not simply lead to the formation of another, or that future treatment "side effects" will not be more detrimental to the attainment of a new equilibrium condition than no treatment.

From the preceding sections, it follows that the science of fluvial hydraulics has not been developed to a level that permits accurate prediction of stream behavior. Judgment is still required in addition to mathematical-statistical analyses. Yet some qualitative predictions are possible since conceptual relationships have been developed for most hydraulic interactions. If streamflow records are available, the investigator can predict at least the trend of future stream behavior.

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NOTATION

A = cross-sectional area of flow—square feet
A' = difference in altitude between concave profile at mid-distance and straight line connecting the ends of profile—feet
D = sediment particle size—millimeters
d = depth of flow—feet
Fr = Froude number
g = acceleration due to gravity—feet per second per second
H = total fall of stream—feet
K_a = coefficient relating sediment load and water discharge
m = mass of water—pounds
p = wetted perimeter—feet
Q = stream discharge—cubic feet per second
Q_s = sediment discharge—pounds
Q_w = water discharge—cubic feet per second
Re = Reynolds number
R = hydraulic radius—feet
r = numerical constant
S = slope—feet rise or fall divided by feet horizontal distance
s = numerical constant
V = average velocity—feet per second
w = top width of channel—feet
γ = specific weight of water—pounds per cubic foot
μ = absolute (dynamic) viscosity—pound-seconds per square foot
ν = kinematic viscosity—square feet per second
ϱ = fluid density—pounds per cubic foot
τ = tractive force—pounds per square foot

Heede, Burchard H. 1980. Stream dynamics: An overview for land managers. USDA Forest Service General Technical Report RM-72, 26 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Concepts of stream dynamics are demonstrated through discussion of processes and process indicators. Theory is included only where helpful to explain concepts. Present knowledge allows only qualitative prediction of stream behavior. However, such predictions show how management actions will affect the stream and its environment.

Keywords: stream dynamics, flow regimes, sediment transport

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Rocky Mountains

Southwest

Great Plains

U.S. Department of Agriculture
Forest Service

Rocky Mountain Forest and Range Experiment Station

The Rocky Mountain Station is one of eight regional experiment stations, plus the Forest Products Laboratory and the Washington Office Staff, that make up the Forest Service research organization.

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Research programs at the Rocky Mountain Station are coordinated with area universities and with other institutions. Many studies are conducted on a cooperative basis to accelerate solutions to problems involving range, water, wildlife and fish habitat, human and community development, timber, recreation, protection, and multiresource evaluation.

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Flagstaff, Arizona
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*Station Headquarters: 240 W. Prospect St., Fort Collins, CO 80526